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Analysis of several test methods about heat insulation capabilities of ceramic thermal barrier coatings

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Abstract

The insulation performance of the ZrO2 ceramic thermal barrier coatings prepared by the oxyacetylene flame spraying process is tested by four methods.Temperature variation curves of the specimen substrate in four different sets of coating thickness are required by testing the temperature of specimen substrate through infrared thermometer and thermocouple connected to a temperature recorder, and the test results arc analyzed with service conditions of ceramic coatings.The results show that,the data obtained by insulation performance vary with different test methods.The four test methods can reflect thermal barrier coating insulation effect and trends in different levels and qualitatively assess the performance of the coating insulation in conditions close to the actual service

Keywords: Thermal barrier coatings (TBCs), Thermal insulation effect, Test, Ceramic coatings ;

1. Introduction

The thermal barrier coating(TBCs) generally refers to a ceramic coating deposited on the metal surface and has a good heat insulation effect, it can effectively reduce the actual operating temperature of the base body to significantly improve its performance and lifetime. Thermal barrier coatings are broadly applied in the field of aviation engines, gas turbines. Ceramic materials have excellent insulating properties (such as ZrO2) [1], which numerous used as the thermal barrier coating material. In order to further improve its thermal insulation properties, a lot of researching work are carried out at home and abroad in recent years [2-13]. The test simulates thermal barrier coating service working conditions to study the thermal barrier coating insulation performance is treated as a very effective way. In order to better assess the coating insulation effect, the rational design of thermal insulation performance test method of thermal barrier coatings is very important. Four different testing methods for ceramic coatings were tested , these test methods were compared and analyzed to study the differences and applications of different test methods for thermal barrier coating insulation performance.

2. Expermental materials and methods

H13 steel is used as the base material of test sample, Ni-Cr alloy (thickness 0.05 mm) is used as adhesion layer and calcium (mass percentage of 5%) stabilized zirconia coating is used as thermal barrier coating surface. The ceramic coating is sprayed by SX-5000 supersonic flame spray equipment, the thermal barrier coating material is heated to a molten state by continuous flame which oxygen-acetylene burner used as the heat source, by means of high-pressure gas atomized into fine particles and sprayed on the surface of workpiece. Then the diamond wheel are used to grind and polish the surface of the coating, ultimately the desired thickness of the samples are obtained. Specific test methods are shown in Table 1.

Table1 Several effect performance test methods of thermal barrier coating insulation

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Test methods	Sample size/mm	Heating equipment	Measuring instruments	Operating methods
1	100×50×6	800W furnace, Furnace wire temperature 1000℃	infrared radiation thermometers	Different thermal barrier coating thickness of the coated sample surface, were placed on a heating source, through resistance wire thermal radiation heating the coated surface, and simultaneously measuring the temperature of the back of sample surface
2	100×50×6	Flame gun, Flame temperature ＞2000℃	infrared radiation thermometers	Different thermal barrier coating thickness of the coated surface of the sample, were placed just above the oxyacetylene flame, the distance of coating surface and flame gun nozzle fixed at 85mm, the intensity of the flame stream is always the same, in order to avoid test error by heating source factors, the coated surface is heated directly by oxyacetylene flame, and simultaneously measuring the back center portion of the heating sample temperature
3	150×150×6	Box muffle furnace, Furnace temperature 1400℃	infrared radiation thermometers	Sample used as the top lid of a muffle furnace observation hole, the coating surface at the same side with furnace chamber, is heated by the heat radiating effect of the furnace chamber, when testing the back center of heating substrate temperature, the furnace temperature is kept constant at 1400 ° C during the test
4	φ20×100（φ8×70 Blind hole）	Tubular-furnace, Furnace temperature 1600℃	Thermocouple + Temperature recorder	Different thickness of thermal barrier coating samples were placed in the Tubular-furnace, after heated by thermal radiation in the furnace chamber for 60s, then air-cooling the sample out of furnace, the whole temperature change of the sample are recorded by thermocouple and temperature recorder during it get in and out of the whole process

3. Results and discussions

3.1 The results and analysis of the insulation effect

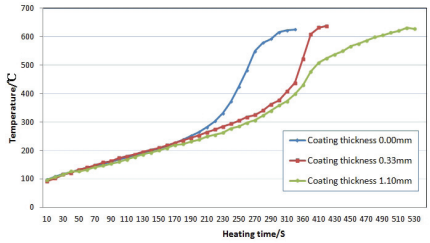


Fig.1. Substrate temperature curve of different thickness of the thermal barrier coated metal(method 1)

Figure.1 shows the insulation effect of three different thicknesses of thermal barrier coatings as 0.00mm, 0.40mm and 1.10mm obtained by test method 1.

From the test results, there is no significant difference in the thermal insulation effect of the three types of samples in 150s. With time, the uncoated specimen's temperature is significantly higher than the coated ones when the time between 250s and 300s. Three groups of specimens with coating thickness as 0.00mm, 0.40mm and 1.10mm, required 300s, 390s and 490s to make the matrix achieved 600 °C, the heating rate of coated sample is significantly lower than the uncoated sample, which indicated the good insulation effect of coating. Because of the simple equipment, this test method can only be described as the ceramic coating insulation of resistance wire thermal radiation. With heating time, the ceramic coating heating and the substrate back surface cooling (convection, radiation) are gradually increased to reach equilibrium, temperature of coated and uncoated back of the sample are consistent, quantitative, long-term stability of the insulation coating is difficult to obtained.

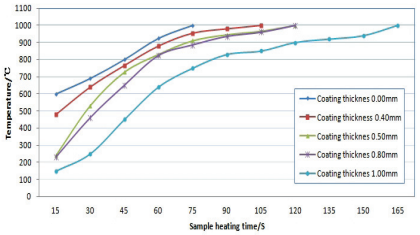
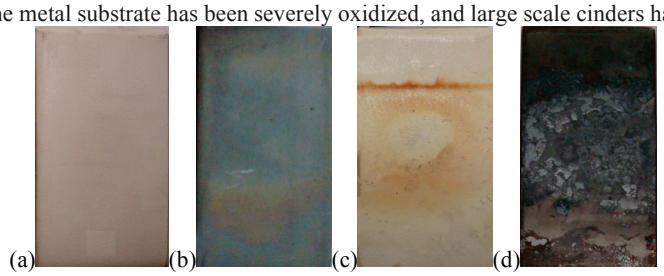


Fig.2. Substrate of the specimen temperature curve of different thickness of metal (method 2)

Figure.2 shows the insulation effect of five different thicknesses of thermal barrier coatings as 0.00mm, 0.40mm, 0.50mm, 0.80mm and 1.00mm obtained by test method 2. From the test results, when the coating is thicker, the temperature of the substrate heating zone is higher, and the time required to reach 1 000 ℃ is longer. The uncoated specimen needs 75s to reach 1000 °C, 0.40mm thick coated specimen needs 105s, 1mm thick coated specimen needs 165s. The second half of 0.5mm thick coated specimen curve is flatten, and time to reach 1000 °C is same to 0.8mm's, which indicated the coating at this thickness has excellent thermal barrier properties.

Figure.3 shows the surface state of the sample before and after test method 2. Before heating, the surface of the ceramic coating sample was a uniform pale white, the metal matrix surface of the sample was uniform color. After heating, the ceramic coating surface of the sample heating zone was red and white colors. Because of the metal substrate temperature is higher than 1000 °C, sample surface of the metal substrate has been severely oxidized, and large scale cinders have emerged.



（a）coating surface before heated（b）substrate surface before heated（c）coating surface after heated （d）substrate surface after heated

Fig.3. Surface morphologies of the sample before and after test (method 2)

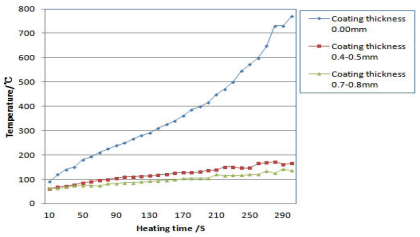


Fig.4. Temperature variation curve of the coated specimen substrate when thermostat at 1400 °C (method 3)

Figure.4 shows the test results obtained by test method 3. From the results of Figure.4, after spray coating processing, due to the low thermal conductivity of thermal barrier coatings, the thermal barrier coating effectively isolate metal substrate and the high temperature of muffle furnace, and effectively hinder the transfer of heat. When heating for 5 minutes, the measured temperature of the sample remains to 200 °C (Fig 4), however heating the uncoated sample for same time, the measured temperature of the sample has reached 770 °C. It fully describes that the coating has obvious thermal barrier effect.

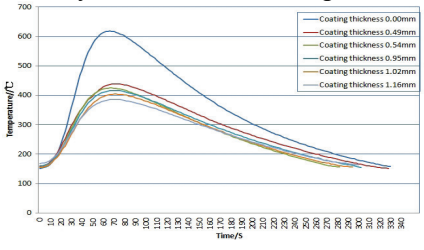


Fig.5. Substrate temperature curve of different thickness of coated specimen (method 4)

Figure.5 shows the test results obtained by test method 4. The test process contains not only heating, but also recording the changing temperature of the sample substrate in cooling process. From figure.5, different thickness of coatings have the same temperature change tendency, the heating rate and cooling rate are substantially the same during the heating process and cooling process. Within the same time, the temperature rising and reducing rate of uncoated samples are significantly higher than the coated samples. The temperatures reached by the metal matrix of different thickness of coated specimen heated for 66s are shown in Table 2.

Table2 Maximum temperature reached by the different thickness of coating specimen metal matrix(test method 4)

Coating thickness /mm	0.00	0.49	0.54	0.95	1.02	1.16
Substrate temperature /℃	618	436	425	416	402	385

The test results obtained from the four kinds of insulation effect of thermal barrier coatings test methods show that a metallic substrate of specimen of the thermal barrier coating the heating rate is significantly lower than the uncoated sample heating rate, and the heating rate of coated specimen are consistent. In the 4 groups of tests, coating thickness and insulation effect is close to the linear relationship, and the coating thickness in the range of 0.49~1.16mm, when the coating is thicker, the insulation effect is better.

3.2 Analysis of the test method of thermal insulation properties

The thermal barrier coating insulation effect of four kinds of test methods are consistent, which suggested that four kinds of test methods all reflect thermal barrier coatings insulation effect better. Because of the heating sources are different or the sample heating in different ways, the thermal barrier coating under ambient temperature of different states is resulted in four significantly varied kinds of testing methods.

In the test method 1, the samples stay in a fully open space(hot swap), when the heating source spreads heat to the sample, the sample also outwardly cooling, and eventually reach a thermal equilibrium temperature (heat flow is equal to outflow), then temperature on both sides are consistent, thermal insulation of coating can not be measured. On the other hand, due to the small electric furnace power, the heating speed of the sample through thermal radiation is very slow. When the thermal barrier coating sample of 0.40 mm is heated for 7 minutes, the sample matrix temperature is just close to 600 ℃. The test method is simple, can qualitatively describe relative comparison value of different thermal barrier coating system(such as different thermal conductivity, thickness and structures) in a period of time during the heating,

Method 2 is essentially the same as Method 1, but the coated surface is directly contacted with flame stream, the heat is transferred more efficiently and increased rapidly, the final equilibrium temperature also greatly improved. Substrate material is seriously oxidized because of high temperature, the infrared measurement is inaccurate. Similarly, the application of scientific value is low.

Compared with method 3 and method 4, the biggest difference is that the back of the sample in a semi-open cooling environment, heat dissipation is controllable, heat flux transferred on coated surface is uniformity and stability. When set a steady heat condition, a certain temperature difference between surface and back to keep the coated sample in a gradient temperature field. The coating insulation is measured by coated / uncoated temperature. Then combine with theoretical calculations and numerical create flat or curved plate heat conduction model to calculate coating insulation value and compare with actual coating insulation by detecting the thermal conductivity of the coating [14]. In addition, temperature changes of two sides are recorded by thermocouples and temperature loggers during the test. Method 3 and Method 4 are limited by furnace power (maximum operating temperature), the sample is difficult to achieve the kind of high-temperature. Therefore, these two test methods typically used to simulate environmental conditions which heating temperature does not exceed 2 000 ℃ (such as hot parts of ultra-high-temperature forming mold [15]).The main difference is that test method 3 is mainly heating on the surface of coatings, sample metal matrix is exposed to the air, and will outwardly cooling while endothermic. However test method 4 sample is completely in tube furnace, sample heating and cooling process boundaries visible, when heated, the metal matrix almost in the endothermic state, and when cooled, the metal matrix basically in a state of cooling. Method 4 is used to analysis heat transfer of thermal barrier coatings and predict substrate temperature to reach, which has important reference value to prefer preparation method of thermal barrier coating and matrix material of components.

4. Conclusion

(1)Due to the difference of heat source strength and sample types of 4 test methods, the experimental data may be different. The heat transfer of latter two methods are stable and uniform and temperature measurement are relatively accurate, they are calculated by theoretical and analyzed by combining numerical simulations and experimental results, which lead to certain scientific application value.

(2)Those four test methods are given a better reflection of insulation effect and temperature trends of thermal barrier coatings. They can be a qualitative assessment of the coating insulation properties when the working condition is close to actual service.

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